

WEAR OF ROTARY PLOWS OPERATING IN A TROPICAL CLAY LOAM SOIL

HUGO GONZÁLEZ¹, NELSON L. CAPPELLI², ALEJANDRO TORO³

ABSTRACT: The wear resistance of rotary plows operating in a clay loam soil was studied. The degree of damage caused to the soil and the amount of mass lost by the tools were determined in order to establish correlations between the physical properties of the soil and the wear mechanisms acting on the tribosystem. Field tests were carried out in 12 plots and a randomized experimental design with 4 levels, 3 replicas per level and 2 passes per plot was applied. The levels relate to the tillage implements employed: rotary tiller, rotary power harrow, small motorized rotary tiller and control (unaltered soil). The highest mass losses were measured in rotary tiller and rotary power harrow's tools, while the small motorized rotary tiller's tools showed generally lower levels of damage. It was determined that the effective contact time between tool and soil, the rotating speed and the sudden impact forces are the most significant factors affecting the wear resistance in field operations. Thirty days after tillage operation the soil samples were taken from each plot at a mean depth of 100 mm in order to determine bulk density, gravimetric moisture content and percentage of aggregates smaller than 5 mm. No significant differences among the values of these properties were found in the experiments. The wear mechanisms acting on the tools' surface are complex and include 2-body and 3-body abrasion as well as the presence of sudden impact forces.

KEYWORDS: abrasive wear; tribosystems; rotary plows; agricultural tool.

DESGASTE DE ENXADAS ROTATIVAS OPERANDO EM UM SOLO FRANCO- -ARGILOSO TROPICAL

RESUMO: Este trabalho apresenta um estudo da resistência ao desgaste de enxadas rotativas, operando em um solo franco-argiloso, com a finalidade de estabelecer correlações entre as propriedades físicas do solo e o mecanismo de desgaste atuando no tribossistema. Foram determinadas a deterioração causada no solo, bem como a massa perdida pelo desgaste das ferramentas. Os experimentos foram realizados em blocos casualizados, com 12 parcelas experimentais, 4 níveis (três tipos de enxadas rotativas - de eixo horizontal, de eixo vertical e autopropelida de eixo horizontal - e uma parcela de solo inalterado), 3 repetições em cada nível e 2 passes por parcela. As maiores perdas de massa das ferramentas foram obtidas, respectivamente, com as enxadas de eixo horizontal e de eixo vertical, enquanto a menor foi obtida com a enxada autopropelida de eixo horizontal. Foi observado que o tempo efetivo de contato da ferramenta com o solo, a rotação angular de operação das ferramentas e as forças de impacto são os fatores que mais afetam o desgaste das ferramentas. Após trinta dias da realização dos testes, foram retiradas amostras do solo de cada parcela experimental, a 100 mm de profundidade, com a finalidade de determinar a densidade aparente, o conteúdo de água e a porcentagem de agregados com tamanho médio inferior a 5 mm. Não foram identificadas diferenças significativas nestas características do solo. Os mecanismos de desgaste que atuam na superfície das ferramentas são complexos e incluem abrasão a 2 e 3 corpos, bem como o efeito das súbitas forças de impacto.

PALAVRAS-CHAVE: desgaste abrasivo; tribossistemas; enxada rotativa; ferramenta agrícola.

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INTRODUCTION

Some of the most common problems caused by inadequate tillage operations include the increase in soil bulk density, macro-porosity loss, compaction, reduced infiltration, hydraulic conductivity, among others (JARAMILLO, 2011). The constitution of a soil is a consequence of the stacking of primary particles (sand, silt and clay) in the form of aggregates, which inevitably leads to a porous structure. Although soil structure is not considered a growth factor for plants, it influences the supply of water and air to the roots, the availability of nutrients in the penetration and the development of roots and soil micro fauna. Also, soil's density is often used as an indicator of compaction and can be related to both porosity and mineralogical aspects, *e.g.*, sandy soils with low porosity have higher density (1.2 to 1.8 Mg m⁻³) than clayey soils (1.0 to 1.6 Mg m⁻³) which have a greater volume of pore space (CABEDA, 1984).

Compaction caused by inappropriate use of agricultural equipment, frequent or heavy traffic or poor soil management can increase soil density in surface horizons, and it has also been suggested that aggregates with average size smaller than 0.5 mm are good indicators of soil structural stability due to their significant role in erosive processes (SAFAR et al., 2011).

Rotary plows are rotational tillage implements that break and mix the soil by using either the tractor's power (rotary tiller, rotary power harrow) or an external power source (small motorized rotary tiller), and the operation typically needs only one pass to let the soil ready for planting (CARRACO & RIQUELME, 2010). These implements can be considered critical under tropical climate conditions due to their strong impact on soil structure and the high erosion risk involved (GLAB & KULIG, 2008; GONZÁLEZ et al., 2007).

The effect of rotary plows is to disaggregate the soil and consequently to increase micro-porosity. Accordingly, the bulk density has been used as a parameter to estimate the degree of soil deterioration (JARAMILLO, 2011; BERNAL et al., 2008; TEIXEIRA et al., 2011). Also, the management of tillage implements demands technical knowledge and precise evaluation of the effects that their intensive use can cause to soil structure (CARVALHO et al., 2007).

It is well established that wear resistance is not an intrinsic material property but an attribute of the tribosystem, which depends on a number of factors such as load, relative speed, temperature, hardness, presence of foreign material and environmental conditions, among others (BHAKAT et al., 2007). When it comes to the agricultural soil-cutting tool tribosystem, complex factors such as the soil texture, spatial variations of soil properties and other unpredictable conditions in the field must also be considered (KAROONBOONYANAN et al., 2007). Abrasive wear of tillage implements results in energy losses and leads to the increase in maintenance delays and production costs, with the consequent negative effects on national economies (BAYHAN, 2006).

Abrasive wear occurs as a result of the dynamic contact between hard protuberances or particles and a softer surface, which causes plastic deformation and displacement of material in ductile tribosystems or cracking and spalling in brittle surfaces (PÉREZ et al., 2010; SUN et al., 2010). Steels, which are the most widely used materials for agricultural tools, have a wide range of wear resistance values depending on their chemical composition, microstructure and thermo-mechanical history. Tools for rotary plows in Colombia are generally made of plain carbon or boron-alloyed steels; boron increases hardenability of hypoeutectoid steels by delaying nucleation of ferrite in the austenitic grain boundaries, and also improves the toughness-to-hardness ratio after tempering treatments (SHIN et al., 2009).

The information available regarding the effect of the use of tillage implements on soil properties is limited and sometimes contradictory due to the large number of variables involved. In consequence, this research focused on the study of the interaction between rotary plows and a tropical clay loam soil in order to quantitatively determine the degree of deterioration that the implements cause to the soil as well as the amount of wear that the soil causes to the rotary plows' tools.

MATERIALS AND METHODS

Tillage tools

Cutter blades from 3 different tillage implements, namely rotary tiller, small motorized rotary tiller and rotary power harrow (Figure 1) were studied. The chemical compositions of the blades are shown in Table 1, where the analysis of all elements (except Boron) was performed by optical emission spectrometry while Boron content was measured by liquid dissolution method. The microstructure of the tools was analyzed in scanning electron microscope and Vickers hardness (HV) measurements were performed by using a universal hardness tester with a load of 62.5 kgf.

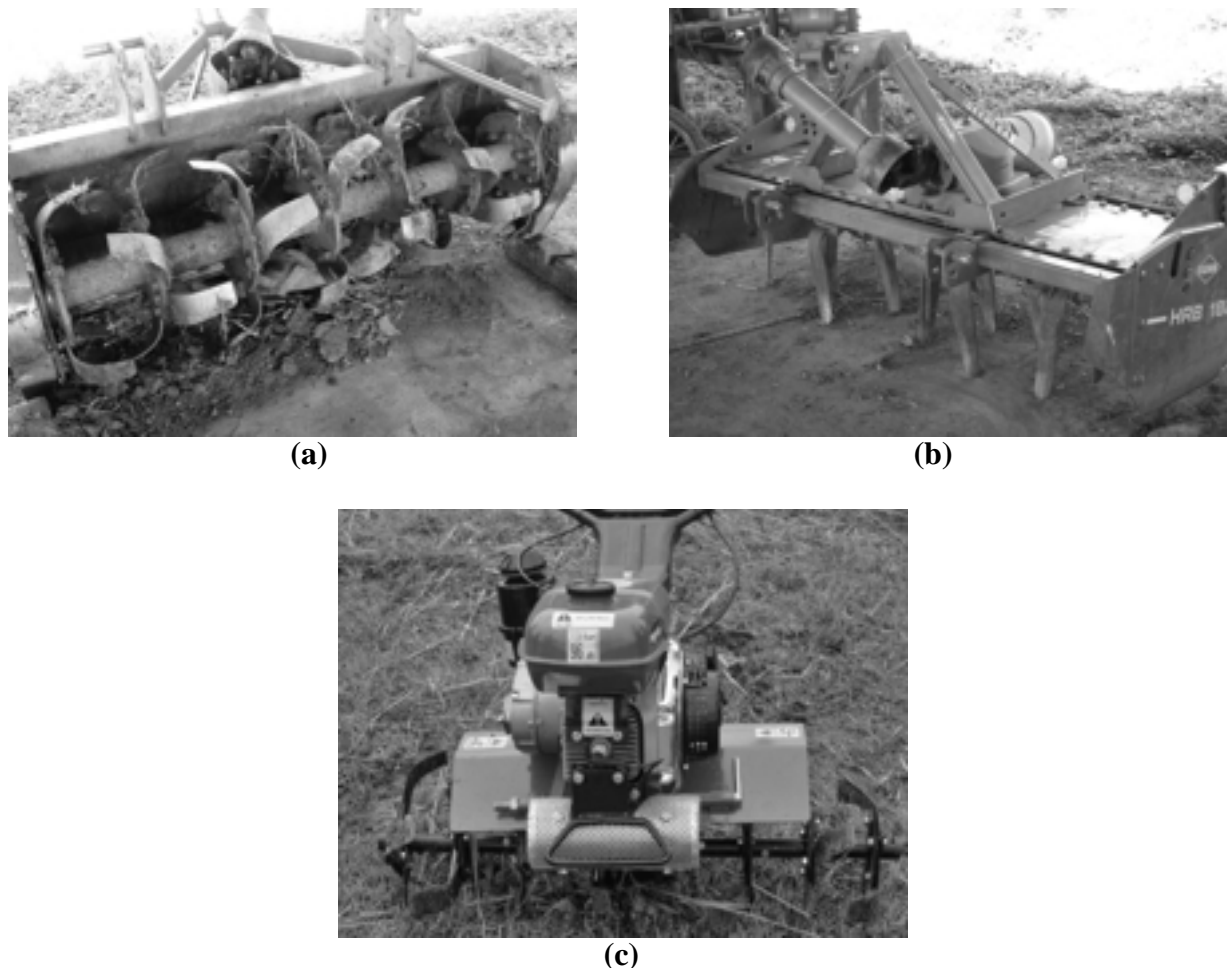


FIGURE 1. Different types of rotary plows studied in this investigation: (a) rotary tiller, (b) rotary power harrow, (c) small motorized rotary tiller.

TABLE 1. Chemical composition of the tool's materials (in wt-% unless otherwise specified).

Tillage implement	C	B	Mn	Si	Cr	Cu	Ni	Others	Applicable designation
Rotary tiller	0.290	0.003	1.228	0.196	0.237	0.010	0.046	0.015 Mo, 0.025 Ti	AISI 15B30
Small motorized rotary tiller	0.280	0.003	1.254	0.204	0.269	0.012	0.040	0.003 V, 0.025 Ti, 0.018 Mo	AISI 15B30
Rotary power harrow	0.127	-	1.256	0.282	0.377	0.175	0.069	0.004 V, 0.034 Ti, 0.027 Mo	AISI 1010, ASTM A36

Study area and field wear tests

The field tests were carried out in an area of tropical dry forest with average annual temperature of 27°C, mean annual rainfall of 1031 mm and altitude of 540 m, belonging to the

Cotové Agricultural Center (6°33'32''N 1°44'43''W), Santa Fé de Antioquia, Colombia. The experimental area presented a clay loam soil with 30% clay, 34% silt and 36% sand, parent alluvial material and average slope lower than 1%. Other initial soil properties were: bulk density (1.27 Mg m⁻³), real density (2.53 Mg m⁻³), total porosity (49.73 %) and penetration resistance (170.10 kPa, to 100 mm depth). The study area has been used for farming for over 5 decades. The specific variety cultivated during the last 10 years is Angleton grass (*Dichantium aristatum*), which was removed from the field with rotary mower before the experiments.

The land was divided into 12 plots with dimensions of 21 × 30 m each in order to apply a randomized experimental design with 4 levels, 3 replicas per level and 2 passes per plot. The levels relate to the tillage implements employed: rotary tiller (TRV), rotary power harrow (TGR), small motorized rotary tiller (TMO) and control (TGO - unaltered soil), and the test samples were the actual tools of each implement. Figure 2 and Table 2 show the experiment details.

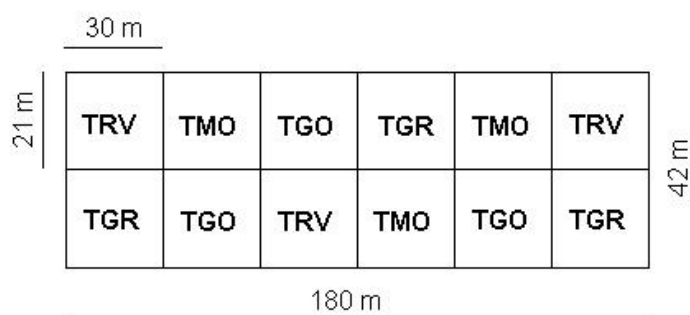


FIGURE 2. Division of the land for the field tests in 12 plots of 21 × 30 m each. TRV: rotary tiller, TGR: rotary power harrow, TMO: small motorized rotary tiller and TGO: control or no tillage operation.

TABLE 2. Experimental conditions for field tests.

Variable	Rotary tiller	Rotary power harrow	Small motorized rotary tiller
Power source	Tractor	Tractor	Self-propelled
Speed (m s ⁻¹)	0.6	0.6	0.2
Theoretical width of work (m)	1.6	1.8	1.0
Rotor frequency (s ⁻¹)	2.4	4.2	2.7
Tangential speed of tools (m s ⁻¹)	3.9	3.6	2.8
Working depth (mm)	150	170	120
Number of tools	36	12	32
Tool type	C-type (135°)	Straight line	C-type (135°)
Required power	30 kW	40 kW	5 kW

The tools' mass was registered before and after the tests by using a scale with resolving power of 0.01 g. In order to standardize the wear results the average values of the measured mass losses were divided by the effective working time of each of the tools. In rotary power harrows (vertical axis) the tools are always in contact with the soil, while in small motorized rotary tillers and rotary tillers (horizontal axis) the contact is intermittent and the effective working time is only half of the total operating time. At the end of the tests, the worn surfaces were analyzed in stereoscopic and scanning electron microscopes in order to identify the wear mechanisms and relate them to the mass loss results. These instruments allow obtaining images with high depth of focus, which is helpful to examine the variations in shape and roughness of irregular surfaces.

Soil analysis

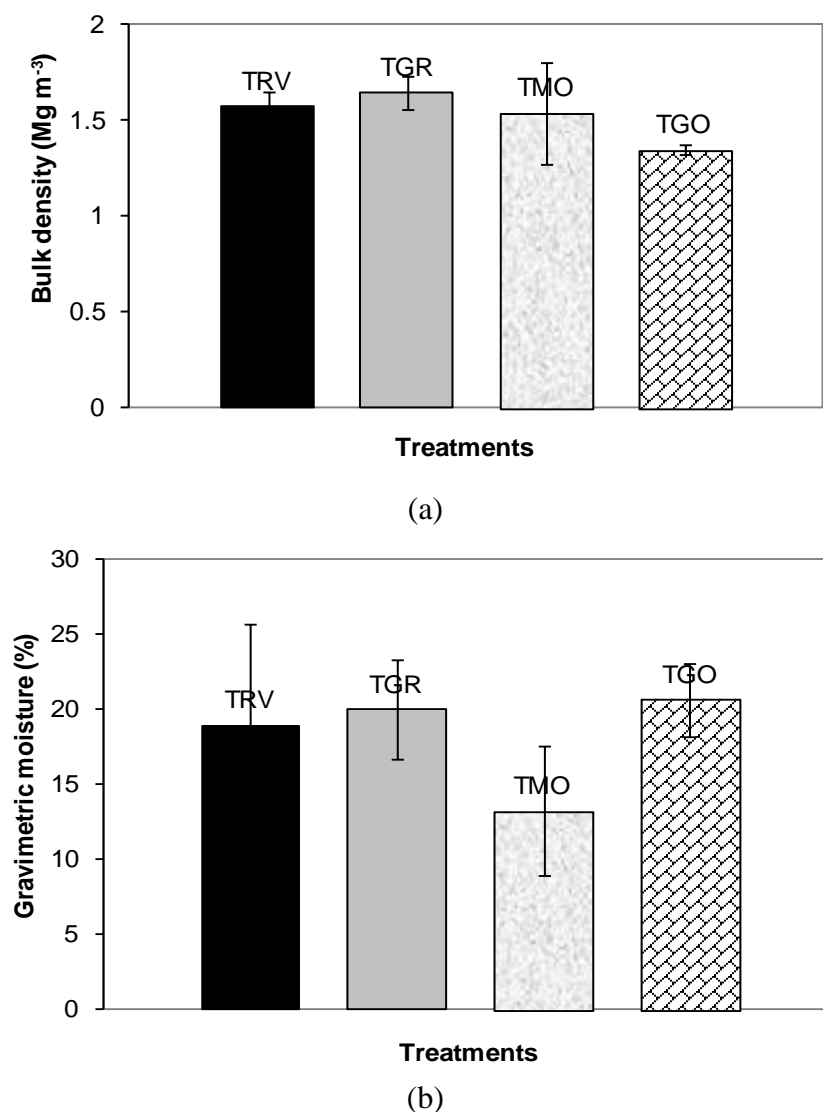
Thirty days after tillage operation soil samples were taken from each plot at a mean depth of 100 mm in order to determine physical properties such as bulk density (ASTM D4531-08),

gravimetric moisture (ASTM D2216–05) and percentage of aggregates smaller than 5 mm following Yoder's method (JARAMILLO, 2011). Field samples were randomly taken at various locations to measure bulk density and gravimetric moisture content (5 samples per plot), as well as percentage of aggregates smaller than 5 mm and texture (1 composite sample per plot). For each physical property measured, an analysis of variance was made with a significance level of $p < 0.05$ to determine whether or not significant changes were introduced to the soil by tillage operations.

RESULTS AND DISCUSSION

Variations in physical soil properties

Figure 3 shows the results of the measurements of physical properties of the soil. It can be seen that the bulk density and the amount of aggregates smaller than 5 mm have a slight tendency to increase after tillage, while the opposite is observed in terms of gravimetric moisture. A higher accumulation of moisture in the areas with no tillage operation is consistent with the evaporation reduction effect of undisturbed vegetation (DEUBEL et al., 2011). Also, the increase in the contents of fine aggregates can be related to higher values of bulk density due to better packing and accommodation of the particles in the soil. The bulk density values measured in all the tests are considered high for soils with medium texture (CORTÉS & MALAGÓN, 1984).



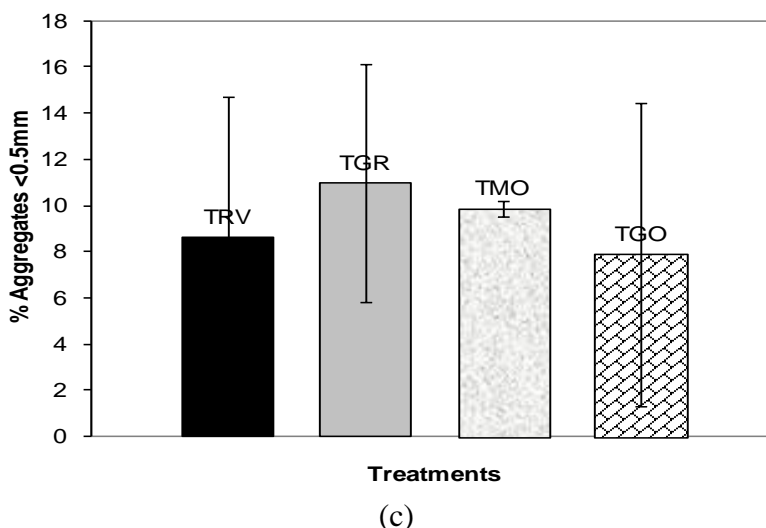


FIGURE 3. Effect of tillage operations on physical properties of the soil. a) Bulk density, b) Granulometric moisture, and c) Aggregates. (TRV: rotary tiller, TGR: rotary power harrow, TMO: small motorized rotary tiller and TGO: control or no tillage operation).

Despite the considerations discussed above, which are based on the analysis of the mean values shown in Figure 3, the statistical analysis of data dispersion revealed no significant differences (within a 95% confidence interval) in bulk density, gravimetric moisture and percentage of aggregates smaller than 5 mm between the soils submitted to the tillage operations and the untreated areas. The F-values obtained were 2.5 for bulk density, 1.68 for gravimetric moisture and 0.21 for aggregates smaller than 0.5 mm, all of them smaller than the minimum value required for significance $F_{(0.05) 3,8} = 4.07$. In other words, at a depth of 100 mm the three treatments with rotary plows virtually did not change the physical properties of the soil. This outcome is relevant because it implies that the selection of the best tillage operation for these particular soil, climate and geographical conditions can rely mostly on aspects such as power consumption, wear resistance and ergonomic considerations. It is worth noticing, also, that in spite of the differences in tangential speed of the tools, no significant effect of this variable was observed in the experiments. This was attributed mainly to the short duration of the tests and to the resilience of the soil (FERNÁNDEZ & GONZÁLEZ, 1998), given that the measurements of its physical properties were measured 30 days after the tillage operations.

Microstructure and hardness of the tools

The chemical analyses revealed that rotary tiller and small motorized rotary tiller's tools are manufactured with AISI 15B30 steel and rotary power harrow's tool is made of AISI 1010 (or, equivalently, ASTM A36) steel. In all cases the microstructure is composed of tempered martensite (Figure 4) with hardness between 458 and 484 $HV_{62.5}$ (Table 3). In rotary tiller and small motorized rotary tiller's tools it is expected the presence of (Fe,Cr) BC precipitates (PERELOMA et al., 2006) which have great influence on mechanical properties of boron-alloyed steels, but their size is too small (< 10 nm in average diameter) to be observed in a scanning electron microscope with thermal-emission electron source as the one used in this investigation. It is worth noticing that, although the carbon content of AISI 1010 steel is lower than that of AISI 15B30 steel, the hardness of rotary power harrow's tools is comparable to that of rotary tiller and small motorized rotary tiller's tools, which can be attributed to differences in the heat treatment of the materials. The hardness and morphology of martensite in AISI 1010 steel are consistent with oil quenching from 900°C while AISI 15B30 steel is typically used in a quenched + tempered condition, the quenching and tempering temperatures being 880-900°C and 350-400°C, respectively.



FIGURE 4. Typical aspect of the microstructure of the tools. a) AISI 15B30 steel used in rotary tiller and small motorized rotary tiller, b) AISI 1010 steel used in rotary power harrow. In all cases the structure is composed of tempered martensite.

TABLE 3. Vickers hardness of the tested tools.

Tillage implement	Hardness of the tool (HV62.5 kgf)
Rotary tiller	458 ± 10
Rotary power harrow	471 ± 10
Small motorized rotary tiller	484 ± 10

Wear resistance of the tools

Figure 5 shows the results of the wear measurements. Despite the fact that the physical properties of the soil did not show statistically significant variations thirty days after tillage operation, the wear response of the tools was very dissimilar depending on the tillage tool used: rotary power harrow and rotary tiller’s tools showed high average wear rates while small motorized rotary tiller’s tools exhibited the best wear resistance among the samples analyzed.

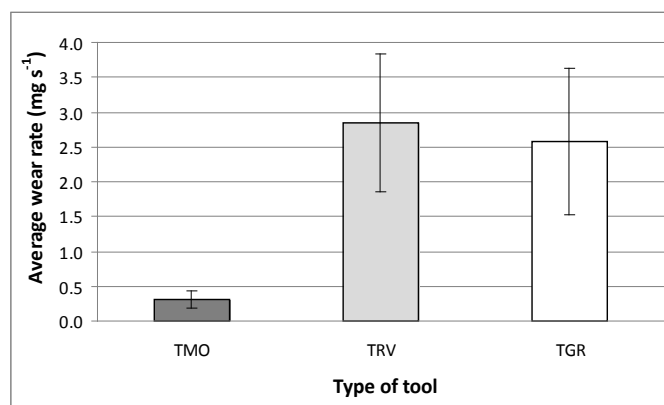


FIGURE 5. Average wear rates (mg s⁻¹) for each type of tool (TRV: rotary tiller, TGR: rotary power harrow and TMO: small motorized rotary tiller).

These results can be discussed in light of the operating conditions of the tools, which are summarized in Table 2. The main factors accelerating the wear process of rotary power harrows are: low number of tools (by design, all the tools in this implement are always in contact with the soil, while in small motorized rotary tillers and rotary tillers they have idle periods), high operating frequency and high working depth. In rotary tillers, the high wear rate is associated mainly to a greater tangential speed of the tools and also to a large working depth. On the other hand, the low wear rate observed in small motorized rotary tiller’s tools is associated to overall mild conditions such as lower operating frequency, tangential speed and working depth. Also, the smaller work

width of the tool is expected to have a positive effect by reducing the total volume of disturbed soil in front of the tool, and consequently causing the effective magnitude of the stresses at the tool's surface to be lower. Finally, the power consumption values also help understand the results since they can be related to the energy transferred from the tool to the soil during the tests: small motorized rotary tiller's tools showed wear rates that are approximately 6 times lower than those measured in the tools of rotary tiller and rotary power harrow, which is consistent with power consumption values that are 6-8 times lower in small motorized rotary tiller than in the other two devices.

Figure 6 shows some examples of the typical features observed at the worn surfaces of the tools. The examination of the tested tools revealed intense plastic deformation, particularly in the regions near to the edges, probably as a consequence of the impact with large particles. Also, micro-plowing and micro-cutting marks were found in the tools of the three types of implements studied, while no evidence of brittle fracture was observed in any area. In small motorized rotary tiller and rotary tiller's tools a significant number of micro-plowing marks were observed in different directions, which indicates the action of both 2-body and 3-body abrasive wear. The former produces long, parallel grooves, while the latter leads to shorter, non-parallel marks caused by soil particles that can rotate and also translate at an angle with respect to the mean direction of movement of the tool relative to the soil.

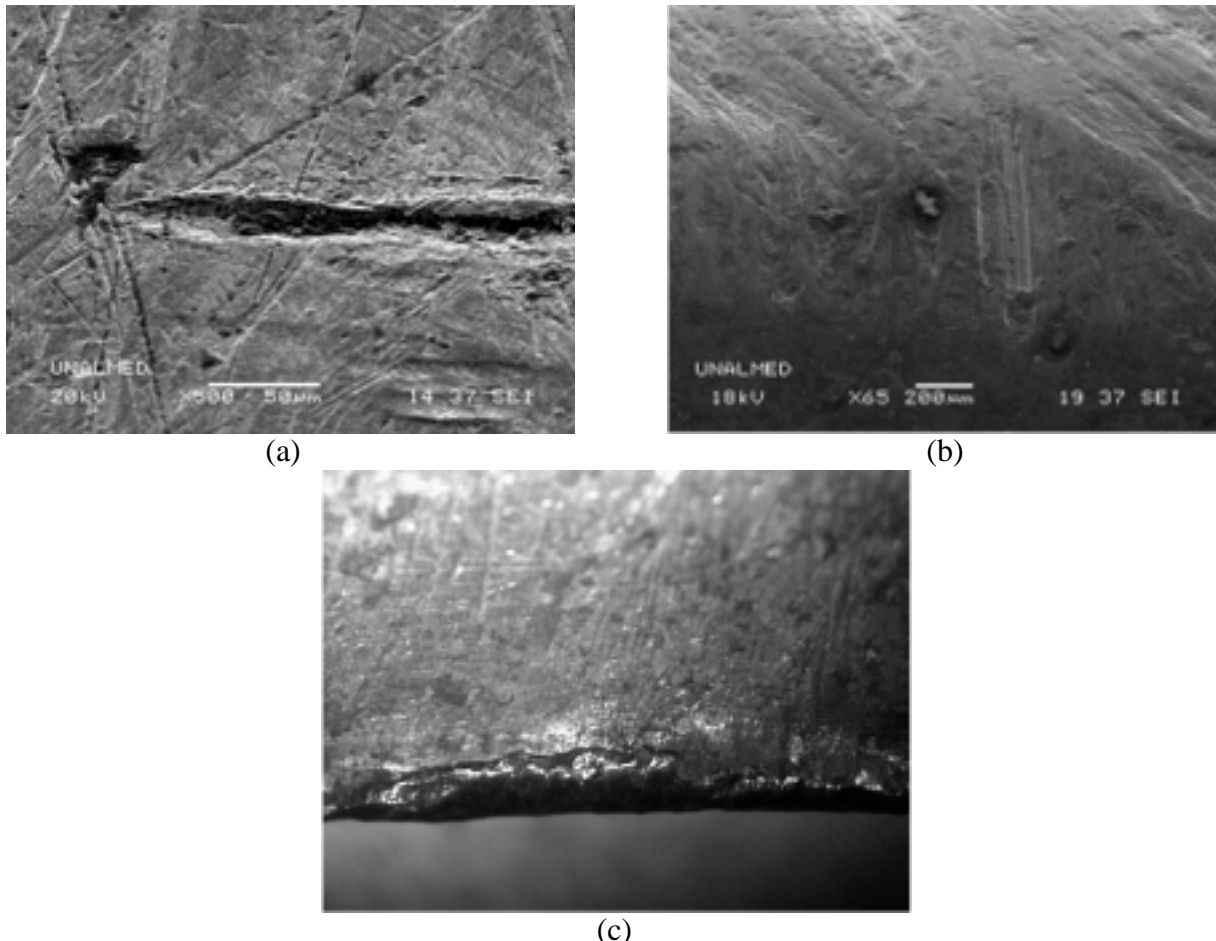


FIGURE 6. Aspect of the worn surface of the tested tools. a) Micro cutting in small motorized rotary tiller's tool (scanning electron microscope image), b) micro plowing in rotary tiller's tool (scanning electron microscope image), and c) plastic deformation on the cutting edge of rotary tiller's tool, possibly caused by impact with a larger particle (stereoscopic image).

CONCLUSIONS

There were no statistically significant differences between the physical properties (bulk density, gravimetric moisture content and percentage of aggregates smaller than 5 mm) of untreated soil and parcels that were tilled with agricultural machinery (small motorized rotary tiller, rotary power harrow and rotary tiller), thirty days after tillage operation. Therefore, for the particular experimental conditions of this study, rotary tillage did not cause negative impacts on the studied soil.

The effective wear rates of the rotary tiller and rotary power harrow's tools were comparable and higher than that of the small motorized rotary tiller's tools, which showed the best wear resistance in the field tests. These differences were attributed mainly to the operating conditions of each type of rotary plow studied instead of being a consequence of variations in the tools material's properties or in the main wear mechanisms acting at the surfaces of the tools.

The wear mechanisms acting at the surface of the tools under field conditions are complex and include both 2-body and 3-body abrasion. Also, the effect of sudden impact forces and distribution of aggregates in the soil are recognized as important variables.

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